Geological Survey
of Canada

# CURRENT RESEARCH
## 2002-D4

# A new approach to downhole seismic imaging, Halfmile Lake, New Brunswick

*G. Bellefleur, C. Müller, D. Snyder, L. Matthews, D. Forsyth, B. Roberts, and D. Tammadge*

2002

Natural Resources Canada
Ressources naturelles Canada
Canada

Catalogue No. M44-2002/D4E-IN
ISBN 0-662-31674-6

A copy of this publication is also available for reference by depository libraries across Canada through access to the Depository Services Program's website at http://dsp-psd.pwgsc.gc.ca

A free digital download of this publication is available from the Geological Survey of Canada Bookstore web site:

http://gsc.nrcan.gc.ca/bookstore/

Click on Free Download.



## Authors' addresses

***G. Bellefleur*** *(gbellefl@nrcan.gc)*
***C. Müller*** *(chmuelle@NRCan.gc.ca)*
***D. Snyder*** *(dsnyder@nrcan.gc.ca)*
***D. Forsyth*** *(dforsyth@nrcan.gc.ca)*
***B. Roberts*** *(broberts@nrcan.gc.ca)*
***D. Tammadge*** *(david_tammadge@hotmail.com)*
*Continental Geoscience Division*
*615 Booth Street*
*Ottawa, Ontario K1A 0E9*

***L. Matthews*** *(mathewl@attglobal.net)*
*Noranda Mining and Exploration Inc. #2800*
*605-5th Avenue S.W.*
*Calgary, Alberta T2P 3H5*

# A new approach to downhole seismic imaging, Halfmile Lake, New Brunswick

G. Bellefleur, C. Müller, D. Snyder, L. Matthews, D. Forsyth, B. Roberts, and D. Tammadge
Continental Geoscience Division, Ottawa

*Bellefleur, G., Müller, C., Snyder, D., Matthews, L., Forsyth, D., Roberts B., and Tammadge, D., 2002: A new approach to downhole seismic imaging, Halfmile Lake, New Brunswick; Geological Survey of Canada, Current Research 2002-D4, 9 p.*

**Abstract:** Downhole seismic data were acquired at Halfmile Lake, New Brunswick, in July 2001, to image known massive sulphide lenses and investigate the potential for a steeply dipping mineralized zone connecting them. The survey comprised two parts designed to provide different imaging capabilities. The first part consisted of four offset VSPs with receivers placed between 265 m and 1300 m depth. A 2.5 km line with 23 shot points was then recorded at receiver positions between 585 m and 815 m. This novel geometry was selected due to its suitability to image the lateral extent of the sulphide lenses at specific depths. The offset VSPs image the vertical extent of the sulphide lenses. Data from both parts of the survey already show several reflections after minimal processing. Reflected P- and S-waves and converted waves (P-S) from the Deep Halfmile lens are observed on several VSPs. Data quality is good with significant improvement expected after further processing.

**Résumé :** Des données de sismique en forage ont été acquises en juillet 2001 au lac Halfmile (Nouveau-Brunswick) afin d'obtenir une représentation graphique de lentilles connues de sulfures massifs et d'étudier la présence possible d'une zone minéralisée fortement inclinée qui relierait les lentilles. Le levé comprenait deux parties, conçues de manière à offrir différentes possibilités d'imagerie. La première partie se composait de quatre profils sismiques obliques ayant recours à des récepteurs placés entre 265 et 1 300 m de profondeur. La deuxième partie consistait en 23 points de tir situés le long d'un profil de 2,5 km avec des récepteurs placés entre 585 et 815 m de profondeur. Cette géométrie particulière a été choisie car elle permet de bien déterminer l'extension latérale des lentilles à un certain intervalle de profondeurs. Les profils sismiques obliques pour leur part fournissent une bonne représentation de l'extension verticale des lentilles de sulfures. Plusieurs réflexions apparaissent dans les données des deux parties du levé après un traitement sommaire. Des ondes P et S réfléchies et des ondes converties (P à S) au contact de la lentille Deep Halfmile sont observées dans plusieurs profils sismiques obliques. Les données sont de bonne qualité et on s'attend à une importante amélioration après traitement plus poussé.

## INTRODUCTION

The downhole seismic imaging (DSI) consortium acquired multi-azimuth, multi-offset vertical seismic profiling (VSP) data at the Halfmile Lake property near Bathurst, New Brunswick in July 2001. Downhole Seismic Imaging is a joint research and development consortium, associating three Canadian mining companies (Falconbridge, Quantec Geoscience, and Noranda) and the Geological Survey of Canada to assess the utility of VSP for exploration of massive sulphide deposits in steeply dipping stratigraphy. The Halfmile Lake sulphide deposits are part of the Gander tectonic zone within the Applachian Orogen of eastern New Brunswick (Fig. 1). The Halfmile Lake area comprises three known sulphide lenses (the Deep Halfmile and Lower Halfmile lenses are shown on Fig. 1), which have a high acoustic impedance when compared to the host rocks (Salisbury et al., 2000). The known sulphides and favourable acoustic properties make this Noranda property an excellent site to test imaging capabilities of the downhole seismic imaging technique. The objectives of Halfmile Lake VSP survey were three-fold: 1) generate a clear seismic image from known massive sulphide lenses using an offset VSP acquisition geometry; 2) image an area of subvertical stratigraphy between the Lower Halfmile and Deep Halfmile sulphide lenses; and 3) gather a data set to test and improve imaging strategies that can be employed at other massive sulphide exploration sites.

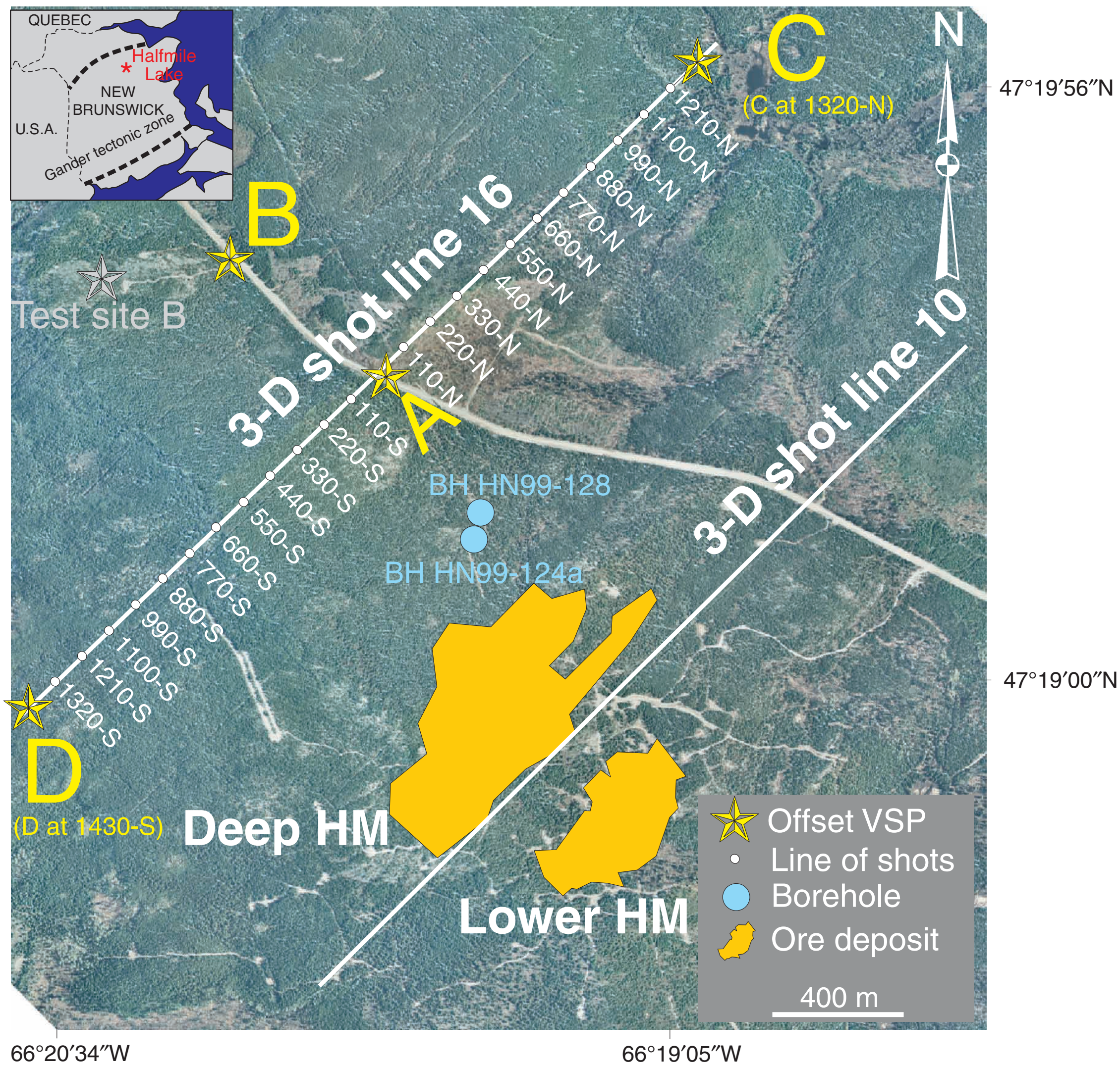


*Figure 1. Acquisition geometry used at Halfmile Lake. The survey was divided into two parts. The first part consisted of four offset VSPs. The shots for this part of the survey are indicated with the yellow stars. Recording depths in borehole HN99-128 ranged between 265 m and 1300 m. For the second part of the survey, shots were distributed along a line between stations 1320S and 1210N. Three shots were fired at each station. Recording depths ranged from 585 m to 815 m. Also indicated are the test site B used during the test survey (grey star) and the position of the recording borehole (HN99-124a). HM=Halfmile*

We present preliminary results which reveal good potential for accomplishing the objectives mentioned above. Some results obtained during a test survey are also shown. After preliminary processing, reflections from the Deep Halfmile sulphide lens can already be observed on some offset VSPs. Reflections from the lenses and stratigraphy are anticipated to become more prominent after full processing of the data.

## SURVEY DESIGN

The acquisition geometry used at Halfmile Lake is outlined in Figure 1. This survey design was based on traveltime modelling results calculated from known sulphide lenses (Lower and Deep), and the area of subvertical stratigraphy connecting these lenses. The modelling approach followed the procedure described in Adam et al. (in press) and was used to determine the optimum shot and receiver locations. The survey comprised two parts. Initially, four source locations were selected (stars marked A, B, C, and D on Fig. 1) at which a total of 104 shots were fired (26 at each site). Shots were then placed along a shot line used during an earlier 3-D seismic survey. At each station along this line (marked 1320S to 1210N on Fig. 1), three shots were fired for receiver positions ranging between 585 m and 815 m.

Borehole HN99-128 was utilized as the recording hole for both parts of the survey because it is the only hole that has remained open in this area of the Halfmile Lake camp. This borehole intersects the Deep Halfmile sulphide lens at a depth of 1336.5 m. Vertical seismic profiling data at that depth should contain prominent reflections and waves converted on the Deep Halfmile sulphide lens.

## TEST SURVEY

A test survey was conducted on June 22 (2001) at Halfmile Lake in borehole HN99-124a (Fig. 1). This 145 m deep, HQ borehole (hole diameter of 3.75 inches (95 mm)) was utilized in order to preserve borehole HN99-128 for the main survey. The top part (0–580 m) of borehole HN99-128 is of HQ diameter whereas the lower part (580–1340 m) is NQ diameter (3 inch (76 mm)). Coupling problems in HQ diameter holes were previously identified in a 3-D VSP survey at Halfmile Lake. Objectives of the test survey were 1) to determine the number of boosters needed to provide sufficient source energy, and 2) to check the response of the tool in the HQ-size borehole. The test survey was also a good opportunity to test a four-level receiver array recently purchased from Vibrometrics Ltd. The new four-level tool was attached to the end of the four-level receiver array of the downhole seismic imaging consortium. Two shot sites were used for the test survey. Site A (Fig. 1) is located next to Otter Brook road while test site B (grey star on Fig. 1) is 400 m west of that road. Shot holes were drilled at the two shot sites (25 at each site) with a Furukawa hydraulic drill. The shot holes were 8 m deep and had a diameter of 3.5 inches (89 mm). Unfortunately, the drill could not access the other shot points proposed in the survey design (sites C and D on Fig. 1). These sites remained untested before the main survey.

Twelve shots were fired during the test, using charges of from one to three pentolite 227 g boosters. Wet- and dry-hole conditions were also tested. For the wet holes, the bottom 1–2 m of the shot holes were filled with water. For both conditions, the shot holes were filled to the surface with drilling dust and sand. Wet-hole conditions provided slightly better results (not shown) but not enough to justify the cost of getting a water tanker and setting water lines to the shot sites for the complete survey. Shot gathers from test sites A and B with three boosters are displayed in Figure 2. Three boosters were required to get clear first breaks. Figure 2 also indicates that the new four-level tool is less noisy than the old four-level receivers; however, the horizontal components of the new four-level tool contain a long coda (a long oscillating sequence) after the first arrivals, here after referred to as "ringing" (Fig. 2a, b). Data obtained using three boosters at site A (Fig. 2a) do not show as significant ringing as data from test site B (Fig. 2b). Part of the strong ringing in Figure 2b is most likely introduced by reverberation within the small hill where test site B was located. Thus, it was decided to move this shot site to a location closer to the road for the main survey (Fig. 1). Data from the new site (Fig. 3) contains less ringing. Other potential causes for ringing include imperfect receiver coupling with the borehole (torsion oscillation) and the response of the new receiver tool. Twenty-one of the shot holes drilled at site A were used in the main survey.

## FIELD ACQUISITION

The recording parameters and acquisition equipment used for both parts of the survey are summarized in Table 1. Equipment and recording parameters were similar to those used in previous downhole seismic imaging surveys (D. Snyder, G. Perron, and K. Stevens, unpub. manuscript, 2001). Only minor adjustments were made to take the acquisition geometry into account. Each receiver level was equipped with a stabilization ring to improve coupling with the borehole. Two sets of clamping arms were used to improve receiver coupling in NQ and HQ parts of the borehole. Long clamping arms (80 mm) were used in the HQ diameter, whereas 40 mm clamping arms were used in the NQ diameter.

Because of highly fractured rocks near the surface, it was decided to preload the shot holes with three boosters (3 x 227 g) and primacord as soon as they were drilled. With this approach, we avoided potential collapse and loss of shot holes prior to or during the survey. The shot holes were drilled and loaded one week before the survey. Seismic caps, necessary to detonate the primacord, were only attached immediately before firing. Preloading of the shot holes may not offer the flexibility of reloading the holes during the survey, especially in case of misfire; however, this approach significantly speeds up data acquisition as shooters saved the time otherwise required for loading.

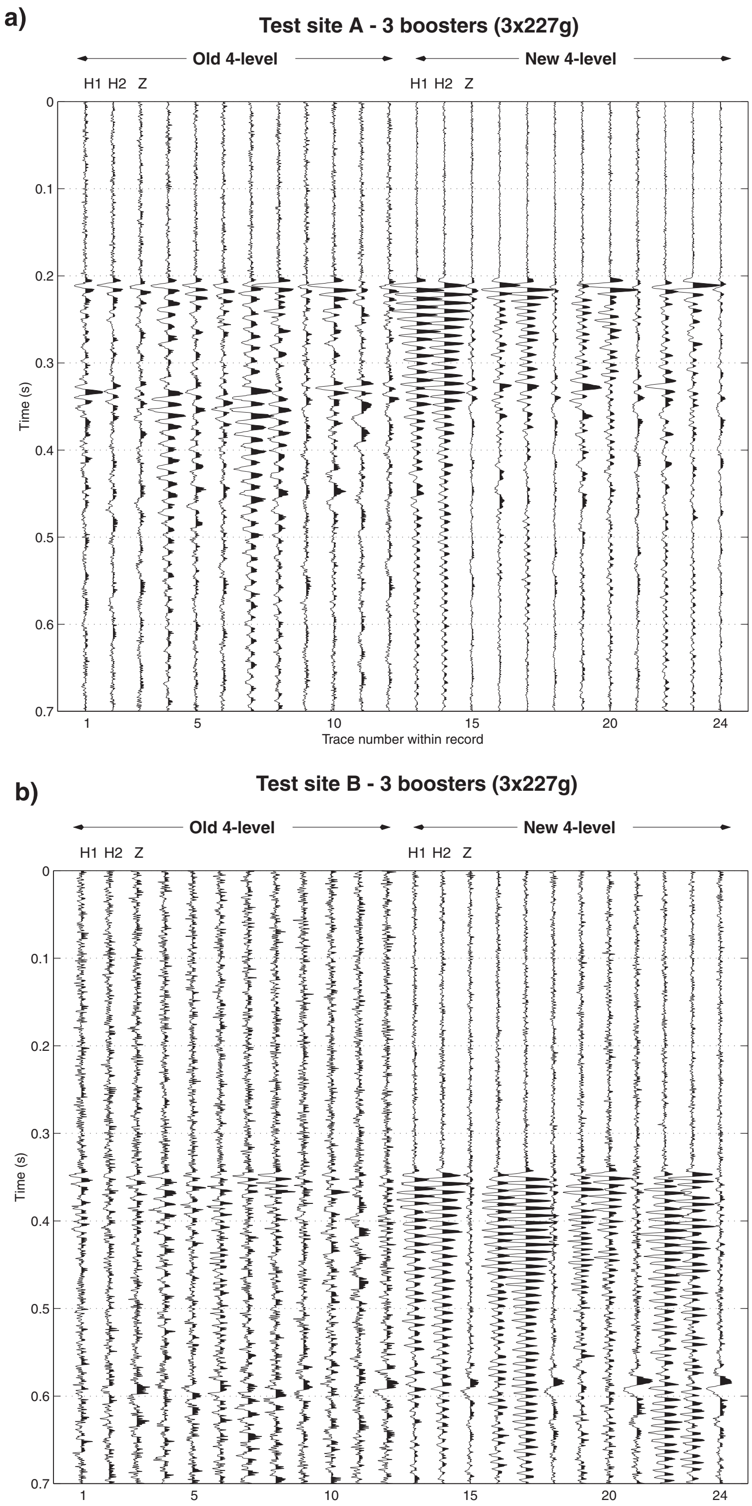


***Figure 2.***

*Shot gathers from test sites **A** (top) and **B** (bottom) acquired with three boosters. The first 12 traces in each record were recorded with the old four-level tool while the last 12 traces were recorded with the new tool. The new four-level tool is less noisy than the old four-level receivers. The horizontal components (H1 and H2) of the new four-level tool show ringing after the first arrivals. Ringing on the horizontal components is less significant for test site A than for test site B.*

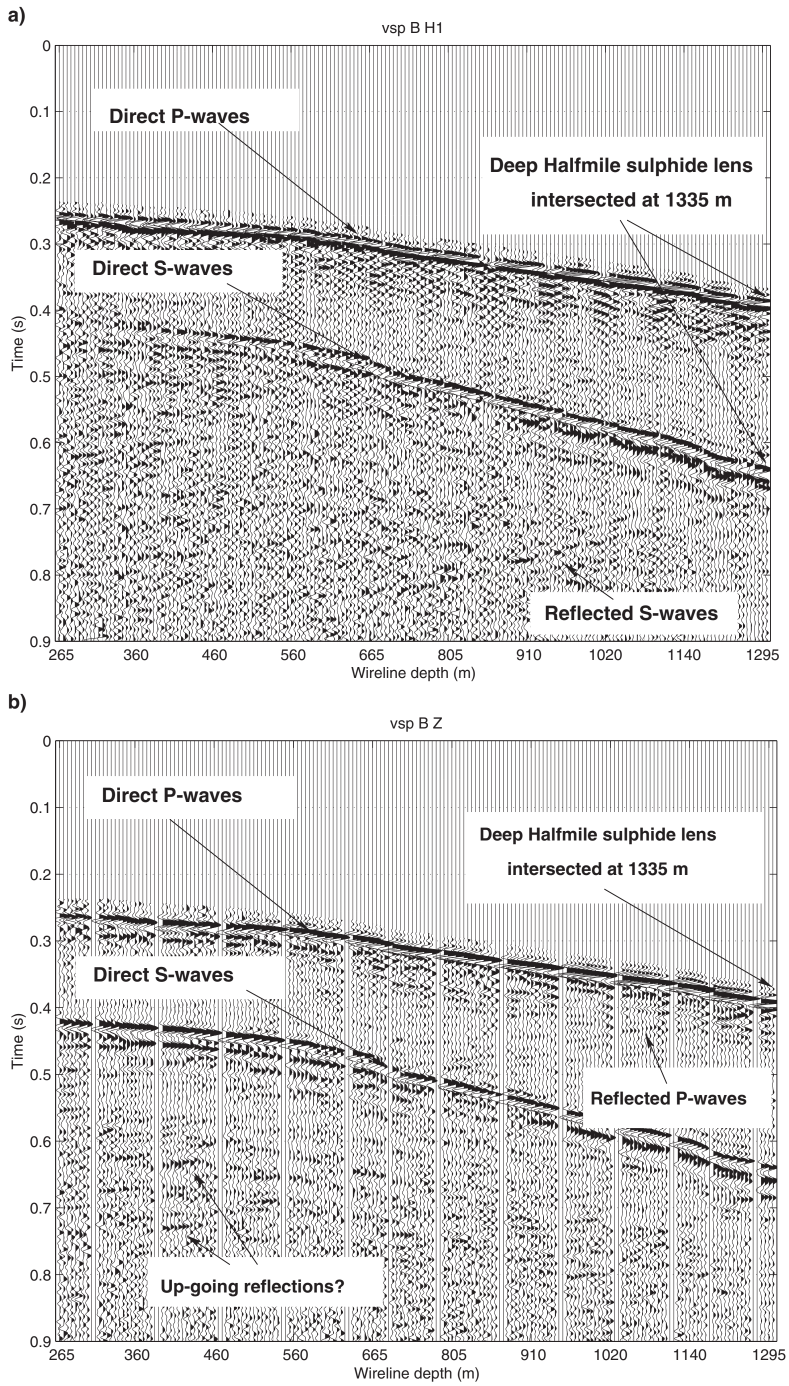


***Figure 3.***

*Vertical seismic profiling data from site B after trace editing, muting signal above direct P-waves arrivals, bandpass filtering and AGC;* ***a)*** *shows the radial component (e.g. the rotated horizontal component pointing towards the shot location;* ***b)*** *shows the vertical component. S-waves (top) and P-waves (bottom) were reflected from the Deep Halfmile sulphide lens intersected at 1336.5 m. These events and other up-going reflections should become prominent after removal of down-going P- and S-waves.*

**Table 1.** Acquisition equipment and recording parameters used at Halfmile Lake.

| | |
|---|---|
| **Offset VSP** | |
| **Acquisition equipment** | |
| Seismograph | OYO Das-1 |
| Receivers | Vibrometric XYZ43CG<br>(eight-level three-component receiver array) |
| Shooting system | Macha shooting system (sites A and B)<br>GSC clock driven shooting boxes (sites C and D) |
| Source | 3 x 227 g boosters, primacord and zero-delay seismic caps |
| **Recording parameters** | |
| Recording depths | 265 m–1300 m |
| Receiver spacing | 5 m |
| Record length | 2.1 s |
| Sampling interval | 0.5 ms |
| Time offset window | -100 ms (pretrigger) |
| **Line of shots** | |
| **Acquisition equipment** | |
| Seismograph | OYO Das-1 |
| Receivers | Vibrometric XYZ43CG |
| Shooting system | Macha shooting system |
| Source | 3 x 227 g boosters, primacord and zero-delay seismic caps |
| **Recording parameters** | |
| Recording depths | 585 m–815 m |
| Receiver spacing | 10 m |
| Record length | 2.1 s |
| Sampling interval | 0.5 ms |
| Time offset window | -100 ms (pretrigger) |

Two shooting systems were used during the survey. The Geological Survey of Canada clock-driven shooting boxes were used at VSP sites C and D (Fig. 1). A Macha shooting system with radio communication and trigger was used at sites A and B and for the line of shots. Relative clock drifts between shooting boxes were corrected using first arrivals recorded with surface geophones located near the recording borehole collar. These drifts were quite significant for some boxes (ranging from 1 ms/day to 72 ms/day). Some drifts were also observed with the Macha shooting system, but they were almost always less than 0.5 ms (sampling rate) and never higher than 1 ms.

Some technical problems occurred during acquisition of the data. The vertical component of the fifth level of the new tool showed a high noise level. Traces acquired with that component were muted. This component had worked fine during the test survey. Spikes also contaminated some shot gathers. Overheating of the seismograph and cross-triggering induced by an electrical storm may have caused most of the spikes. Recording was stopped as soon as spikes were observed on the data. One GSC shooting box lost time during acquisition and had to be replaced, but no data were lost.

## FIRST RESULTS

In the following sections, we present data acquired at Halfmile Lake with preliminary processing applied. This included trace editing, muting of signal above direct P-wave arrivals, bandpass filtering (5-25-105-125 Hz), and AGC gain (window of 0.25 s). The horizontal components were transformed by applying a rotation matrix, which maximizes P-wave energy on one component (hereafter called the “radial component”), to determine the geophone orientation in the borehole. Preliminary rotations of the horizontal components were applied to the offset VSP data. Where required, drifts of the clock-driven shooting boxes were also corrected (sites C and D).

### *Offset VSP*

Figure 3 shows the VSP data while shooting at site B. On this figure, the vertical and one of the horizontal components (radial component) are shown. Both components show strong down-going P- and S-waves. The radial component contains a clear reflected S-wave while a reflected P-wave is observed on the vertical component. These reflections converge with the direct arrivals at 1336 m, where the borehole intersects the Deep Halfmile sulphide lens and thus originate from the ore zone.

Data from the radial component from VSP shot site C are shown in Figure 4. Direct P-waves are the strongest events on this component. Down-going S-waves are weak and observed locally between 560 m and 860 m. Recent modelling studies suggest that massive sulphide ore deposits should generate a prominent P-wave to S-wave conversion (Bohlen et al., in press). Interestingly, P-to-S converted reflections originating from the Deep Halfmile lens is clearly visible in Figure 4.

### *Line of shots*

This part of the survey was recorded after completion of the offset VSP surveys. The receivers were placed between 585 m and 815 m, with a spacing of 10 m. The final decision on where to position the receivers was taken in the field and based on the following considerations. First, the HQ part of the hole was avoided. Second, the 585–815 m depth range provided the best quality data on records from the three VSP shot sites located along the shot line (sites A, C, and D). In addition, preliminary modelling results show that this depth range is appropriate for imaging the area of subvertical stratigraphy between the Lower Halfmile and Deep Halfmile lenses.

Figure 5 shows traces recorded from shot station 880S (*see* Fig. 1 for shot location). The horizontal components (H1 and H2) are unrotated. All components show clear direct P- and S-waves. The vertical component (Z) contains reflections which are clearly visible on the raw data (Fig. 5a). The reflections are prominent after bandpass filtering and AGC (Fig. 5b). Several records from other shot locations also contain clear reflections on the vertical component (not shown).

## FUTURE WORK

### *Processing*

More elaborate processing needs to be applied to the acquired data sets. There will be a particular focus on rotation of the horizontal components and removal of the direct P- and S-waves. Some care will have to be taken when removing the S-waves as some reflections are observed closely following or intersecting these waves.

### *Imaging*

Three-dimensional imaging and/or migration of three-component VSP data acquired in the crystalline crust is a relatively new field. Thus three different approaches to imaging will be tested with the processed data, i.e. classical diffraction stack migration, diffraction coherency migration, and polarization stack migration. A description of the methods can be found in Müller (2000). These methods will be applied separately to the offset VSPs and the line of shots as well as to a combined data set. The reflected S-waves and P-to-S converted waves will also be tested for imaging purposes.

### *Inversion*

If feasible, an investigation of the amplitude versus offset (AVO) trend of the ore reflection will be conducted, since true amplitude processing is intended. The amplitude versus offset trend will provide insight into the composition of the ore deposit and will demonstrate the extent to which amplitude versus offset inversion can be applied in upcoming studies.

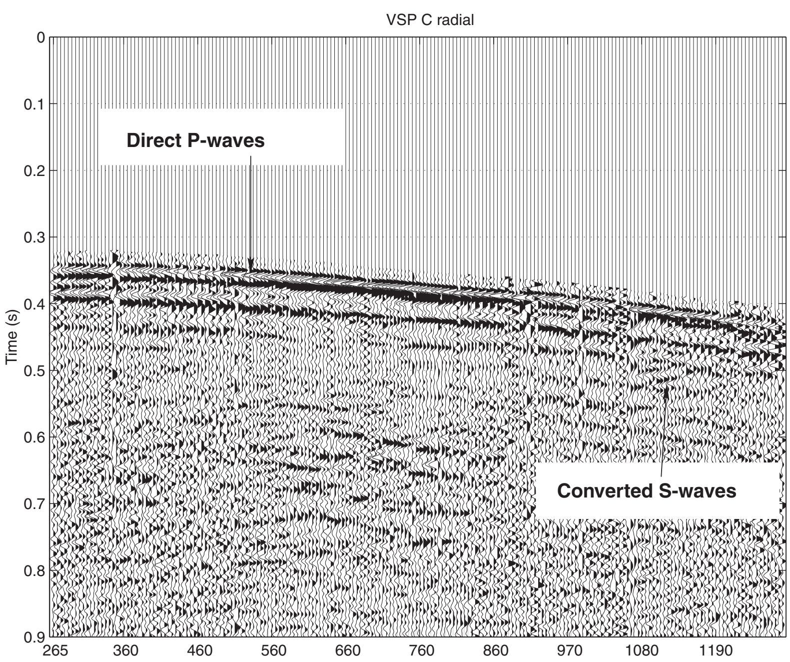


***Figure 4.***

*Radial component from VSP site C after bandpass filtering and AGC. The up-going reflection indicated by the arrow is an S-wave, converted at the Deep Halfmile sulphide lens (P-to-S conversion, approximate velocity 3000 m/s).*

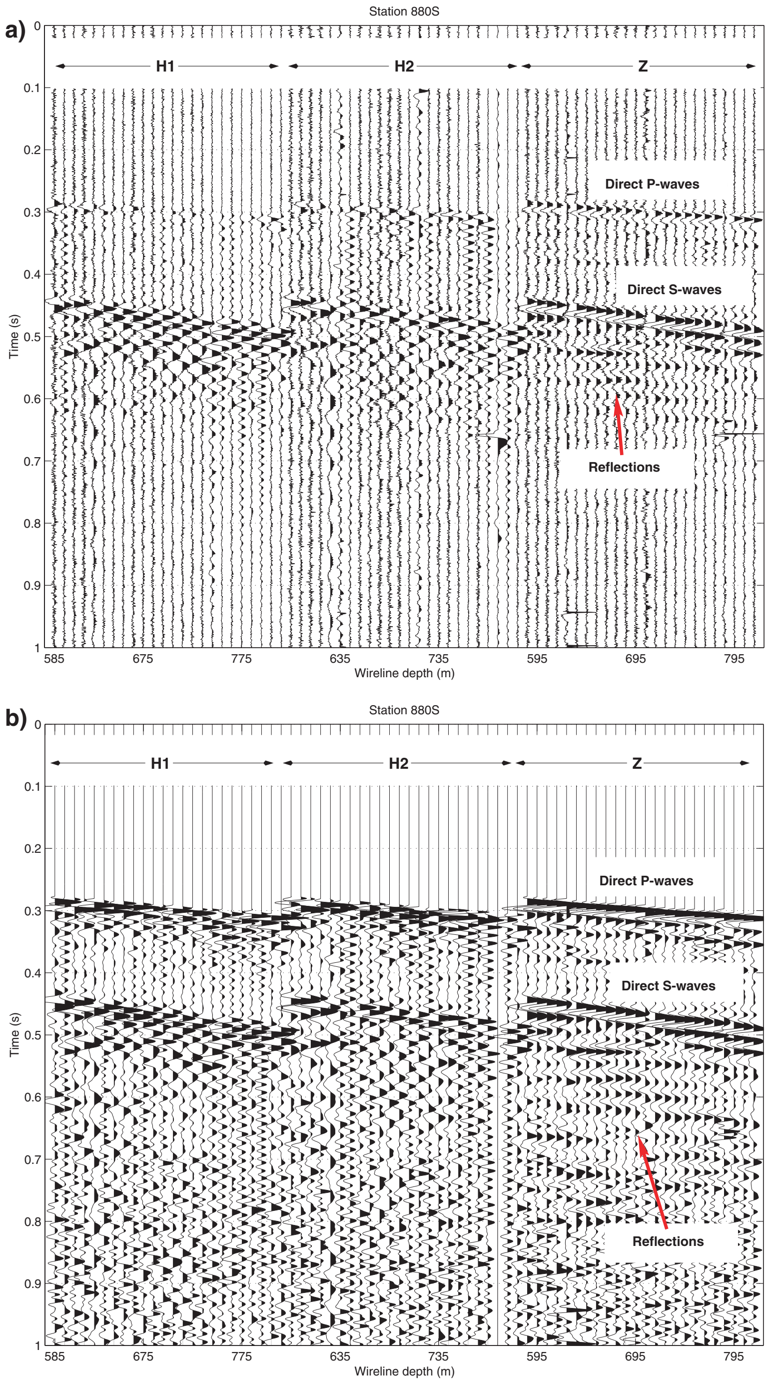


***Figure 5.***

*Data collected from station 880S for geophone positions ranging between 585 m and 815 m. **a)** Raw data shows direct P- and S-waves and reflections apparent on the vertical component. The reflections become more prominent after **b)** bandpass filtering (5, 25, 105, 125 Hz), muting signal above the first breaks and application of AGC The horizontal components (H1 and H2) are unrotated.*

## CONCLUSIONS

Two acquisition geometries were tested at Halfmile Lake in order to image the known upper and lower Halfmile Lake lenses and investigate the subvertical stratigraphy connecting them. The surveys were designed to provide lateral (line of shots) and vertical (VSP) mapping of the targeted ore deposits. Both geometries provided good quality data and clear reflections after only minimal processing.

The line of shots data set shows prominent reflections close to the down-going S-wave arrivals. At this stage, it is not possible to identify the origin of these reflections.

The P- and S-waves reflected from the Deep Halfmile lens are observed on several VSPs. The radial component from VSP shot site C shows a P-to-S converted reflection, also originating from the deposit.

By simply observing converted waves originating from the ore, the experiment supported recent modelling studies predicting this effect. At the current stage we are unable to say if the subvertical stratigraphy between the deposits will be imaged; however, reflections observed on both data sets are an essential requirement to provide successful imaging of the massive sulphide lenses. Further processing will likely improve the data quality. The survey will provide data sets suitable for testing and improving imaging strategies that can be employed at other massive sulphide exploration sites.

## ACKNOWLEDGMENTS

We thank Larry Petrie and Robert Banville of Noranda (Bathurst) for logistical support provided for this downhole seismic imaging survey. We thank Noranda for permission to release these results.

## REFERENCES

**Adam, E., Bohlen, T., and Milkereit, B.**
in press: Vertical seismic profiling at the Bell Allard orebody, Matagami, Quebec; *in* Seismic Exploration Methods, (ed.) B. Milkereit, D. Eaton, and M. Salisbury; Society of Exploration Geophysicists.

**Bohlen, T., Müller, C., and Milkereit, B.**
in press: Elastic wave scattering from massive sulfide orebodies: on the role of composition and shape; *in* Hardrock Seismic Exploration, Society of Exploration Geophysicists Developments in Geophysics series.

**Müller, C.**
2000: On the nature of scattering from isolated perturbations in elastic media and the consequences for processing of seismic data; Ph.D. thesis, Christian-Albrechts-Universitat of Kiel, Kiel, Germany, 158 p.

**Salisbury, M., Milkereit, B., Ascough, G., Adair, R., Matthews, L., Schmitt, D.R., Mwenifumbo, J., Eaton, D.W., and Wu, J.**
2000: Physical properties and seismic imaging of massive sulfides; Geophysics, v. 65, p. 1882–1889.

Geological Survey of Canada Project 970012-A1